Real-Time Visualization of Massive Movement Data in Digital Landscapes

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Abstract

Due to continuing advances in sensor technology and increasing availability of digital infrastructure that allows for acquisition, transfer, and storage of big data sets, large amounts of movement data (e.g., road, naval, or air-traffic) become available. In the near future, movement data such as traffic data may even be available in real-time. In a growing number of application fields (e.g., landscape planning and design, urban development, and infrastructure planning), movement data enables new analysis and simulation applications. In this paper, we present an interactive technique for visualizing massive 3D movement trajectories. It is based on mapping massive movement data to graphics primitives and their visual variables in real-time, supporting a number of visualization schemes such as sphere, line, or tube-based trajectories, including animations of direction and speed. This generic technique enhances the functionality of VR and interactive 3D systems using virtual environments such as digital landscape models, city models, or virtual globes by adding support for this important category of spatio-temporal data.

1 Introduction

Interactive 3D virtual environments serve as efficient tools that allow for visualizing, exploring, analyzing, and simulating spatial environments and phenomena in a large number of application fields including geodesign. In particular, they enable users to explore geospatial and spatio-temporal data as well as to analyze and reason about dynamics and processes.

While there is a large number of methods and techniques for real-time 3D visualization of static 3D spatial models, which are composed by elements such as terrain, buildings, and vegetation, the visualization of dynamic phenomena such as movement is still a key challenge. Dynamic phenomena are typically described by spatio-temporal geodata. Movement data represents a major category of dynamic phenomena relevant to a large number of application domains.

To motivate and illustrate our technique, we focus on air-traffic movements as a specialized but generic example of massive movement data. Air-traffic movements gain increasing attention both in the public as well as for air-traffic management and planning. Besides infrastructural requirements, the increasing amount of flights also impacts regional population in numerous ways, e.g., with respect to fine dust pollution loads or noise pollution, especially in the surrounding of major airports. Air-traffic movements can be described by movement trajectories given by high-resolution, spatio-temporal (3+1D) data. Real-time processing and visualization of massive movement data allows us to explore and analyze trajectories and correlate them, e.g., with landscape characteristics or elements. For example, flight route planning depends on local weather conditions whereas sound propagation varies with respect to the landscape surface (e.g., water or forested regions).

In addition to applications for air-traffic management or for the effective communication of air-traffic for public purposes, interactive visualization of occurred or simulated air-traffic can also be useful for reasoning about spatial processes in landscape planning and design. This includes visualization of recorded real air-traffic, air-traffic simulation, and differences between both. For example, interactive visualization can support decision making concerning the impact of different flight routes on living quality in the affected areas, which runways can be used at which time spans, or the construction of airport facilities.

Previous Approaches for the Visualization of Movement Data

There are a number of research projects concerned with the visualization of movement trajectories. They can be roughly categorized into (a) 2D or 3D visualization of movement trajectories, e.g., in the field of air-traffic visualization (HURTER ET AL. 2009, KLEIN ET AL. 2014) and (b) visualization of aggregated data using density maps of moving objects (WILLEMS ET AL. 2009). However, there is a lack of techniques that allow for combining these approaches and integrating visualization of massive movement trajectories into detailed virtual landscape models, city models, or virtual globes.

A lot of research has been conducted with respect to the space-time cube (HÄGERSTRAND 1970), which depicts temporal aspects of movement data or spatio-temporal data in general by mapping time onto a visual axis (e.g., ANDRIENKO ET AL. 2003, KRAAK & KOUSSOULAKOU 2005, or KRISTENSSON ET AL. 2009). This method is well suited for conveying and exploring temporal relationships between individual or a limited number of trajectories in detail and is often used in conjunction with cluster analysis (ANDRIENKO ET AL. 2009). However, this technique struggles with problems of visual clutter and perspective distortion when faced with large unclustered trajectory data sets. It is also not easily applicable for a visualization of true 3D movement data since the 3rd dimension is already used to visualize the temporal aspect.

Further research has focused on the visualization of multi-faceted movement data such as attributed movement trajectories. For example, a stacking-based or wall-like approach has been proposed to visualize the multiple attributes of trajectories (TOMINSKI ET AL. 2012) and was also applied to the space-time cube visualization (ANDRIENKO ET AL. 2014). Furthermore, visualization and interaction techniques have been developed to explore attribute values using density map approaches (SCHEEPENS ET AL. 2012).

Contributions

This paper presents an approach for real-time processing and visualization of massive movement data represented by a set of attributed trajectories. It enables interactive filtering and attribute mapping, supports a variety of traditional visualization metaphors such as density maps for aggregated data, and can be integrated into VR and interactive 3D systems by adding support for this important category of spatio-temporal data. It combines real-time computation and processing with real-time, hardware-accelerated rendering using consumer graphics hardware. This approach has a number of advantages: (1) it enables interactive spatio-temporal filtering and exploration for visual analysis of massive movement data without preprocessing, and (2) supports the dynamic configuration of data mappings and visualization of per-trajectory and per-sample attributes, as well as for aggregated values.

The remainder of this paper is structured as follows. Section 2 presents our approach for a real-time processing pipeline for massive movement data. Section 3 discusses results and application to the field of digital landscape architectures and concludes the paper.

2 Approach

Figure 1 shows a schematic overview of our approach and its integration into a visualization pipeline reference model (WARE 2000). It enables the integrated management, real-time processing, and visualization of massive aircraft trajectories within digital landscapes by shifting the workload of each task to massive parallel processors. Our approach consists of three major components:

Data Management and Streaming. This component supports the handling of two different categories of raw input data that can be managed and accessed using our system: (1) air-traffic data that is captured, e.g., by radar, can be streamed and (2) historic data sets, which can be loaded from local or web sources.

Real-time Data Processing. Using massive parallel processing based on computer graphics hardware, air-traffic trajectories can be filtered with respect to spatial and temporal characteristic in real-time without the modification of its data representation. Also, data analysis on trajectory attributes and aggregation methods can be applied in real-time to derive modified data representations (e.g., density maps that can amend the visualization).

Interactive Data Rendering. Based on the compact data representation, a novel real-time rendering technique supports interactive visualization of trajectories generating 3D geometry and mapping its attributes to color, texture, and shape, both static and animated (BUSCHMANN ET AL. 2014). The resulting rendering can be distributed and accessed using standardized web-services (DÖLLNER ET AL. 2012) and embedded into service-oriented architectures and processing chains.

The following sections cover trajectory rendering and aggregation in more detail since they represent the major building blocks of our approach.

2.1 Real-Time Trajectory Rendering

To support visual analysis of real-time data such as trajectories of moving objects created by remote sensing and massive historic data sets, techniques for the interactive visualization and exploration of large sets of trajectories are required. To emphasize on the spatial nature of the data and to analyze correlations between data and the respective geographic reference space, such a visualization technique requires embedding into a geovirtual environment.

In this context, the visualization of trajectory attributes (e.g., direction or speed) plays an important role for analyzing and understanding movement data. This is often established by mapping attribute values to visual properties of rendering primitives such as color or size. In addition to that, the visual representations can also be used to express further contextual

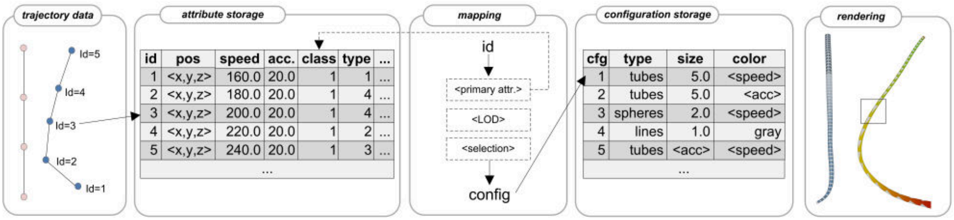

Fig. 1: Schematic overview of data representation, visual configuration, and attribute mapping scheme for visualizing trajectories.

information. For example, different geometric representations, such as spheres or tubes, can be used to distinguish between different classes of trajectories. This supports visual differentiation using focus+context techniques or to give visual feedback to user interactions.

In the following, a real-time visualization technique is described that uses a dynamic mapping approach. It enables the modification of visual presentations of massive input data interactively. For example, different *visualization configurations* can be chosen based on (1) the attribute values, (2) the result of an analysis function (e.g., clustering), or (3) as a response to user input such as selection and filtering. As a result, the visual presentations of displayed data can be changed in real-time without requiring preprocessing data or recreating geometry. This enables distinguishing between different types of trajectories, highlighting certain parts of single or multiple trajectories, or examining parts of the dataset in higher levels of detail. This is especially useful in the context of interactive analysis systems, since it enables users to visually explore datasets by assigning distinct visual styles to different aspects of the data, thereby allowing them to gain insight into the data and to understand its structure.

Data Representation. All attribute values of an input dataset are stored in a *central attribute storage buffer* that is streamed to the GPU. This buffer is accessed to fetch the attribute values of a specific trajectory node at any time during the rendering process using a unique identifier. It further enables a compact data representation and efficient management, as well as optimizes the performance of dynamic data pulling.

Data Mapping using Visualization Configurations. Visualization configurations define how attribute values are mapped to visual properties such as geometry type, size, or color. In our prototypical implementation, a number of configurations are stored in a single *configuration storage buffer* on the GPU. During rendering, (1) a configuration used for each node of a movement trajectory is determined; (2) the respective configuration is fetched from the configuration buffer, and (3) used to map the attribute values to visual properties accordingly.

Dynamic Data Pulling. During rendering, a unique identifier provided on a per-vertex basis, references the respective attribute data. This identifier is used to look up the actual attribute values of the node from the attribute data storage. First, the value of the *primary attribute* is fetched for the current node and used as initial setting for a mapping configuration. This configuration can also be influenced by level-of-detail or specific user selection. For example, the configuration can be chosen (1) by a classification that dissects a dataset into several categories (e.g., clusters of similar movement patterns), (2) by distinct phases of movements (e.g., slower or faster movement), (3) by user interaction (e.g., to visually distinguish between selected and unselected trajectories), or (4) to differentiate between different focus and context regions. The level-of-detail is applied by modifying the respective configuration based on the distance to the virtual camera, e.g., to reduce the geometric complexity for improving rendering.

Geometry Creation and Attribute Mapping. After the configuration has been determined, it is fetched from the configuration storage buffer and applied to the current node. First of all, the mapping configuration selects the type of geometry that is to be rendered (e.g., spheres, lines, or tubes). In addition to that, it also describes the parameterization of this geometry and its visual properties (e.g., tessellation factor, size/radius, color, and texture). Each of these properties can be assigned either a static value from the configuration or can be set to map the value of a node attribute. In the latter case, the value of the specific attribute is fetched and applied to the visual property. After the geometry and its visual properties have been configured, the actual geometry is created on-the-fly and passed on for rendering.

Real-time Rendering. Finally, the generated geometry is rendered by assigning visual properties such as color and texture to the rendering primitives. Additional effects such as texture animation are also performed during this step. Afterwards, post-processing effects are applied to enhance the visual quality of the final rendering, e.g., global illumination effects or enhancement of depth-cues.

2.2 Real-Time Aggregation and Density Maps

In addition to real-time rendering of individual trajectories, which can be used to interactively inspect individual movements, aggregated representations (density maps) of movements can facilitate understanding of movement patterns, i.e., the overall traffic volume in an area over a specific period of time or the change of movements between different time periods (e.g., daytime and nighttime). Aggregated density maps are also useful for comparing individual trajectories to aggregated data: (1) by visualizing individual trajectories in combination with aggregated data representations, outliers can be detected visually or (2) the relation of trajectories to apparent data clusters can be emphasized.

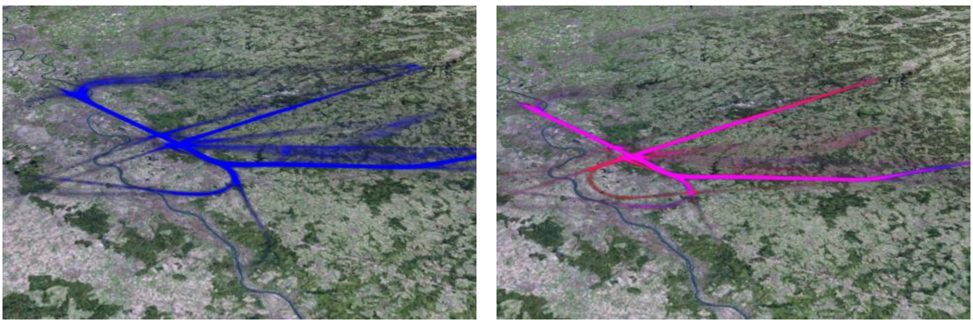

Fig. 2: Visualization of density maps of moving objects: aggregated view on air-traffic movements over the time period of a week (left), comparison of two time periods using distinct color channels red and blue (right).

In our approach, movement data is aggregated automatically. The aggregation is performed in real-time using the GPU and takes the following aspects into account: (1) the current area-of-interest, (2) selected time period, and (3) further filtering options. All of these aspects can be interactively controlled by the user. The result can be a single or multiple density maps that reflect the amount of movements. These density maps can be visualized using heat maps by mapping density to color and can be embedded in an underlying map or virtual landscape model (Figure 2).

Using interactive temporal exploration methods, multiple time periods can be selected simultaneously to visually compare their respective traffic volumes. These can be visualized simultaneously by displaying the individual density maps using separate color channels, or by using a difference map that directly encodes the distances between two density maps by color.

3 Results and Conclusions

This paper presented a novel approach for supporting real-time processing and visualization of massive movement trajectories within interactive VR and 3D systems. It visualizes collected, real-time, or simulated movement data by individual attributed trajectories or by aggregated density maps. The presented technique facilitates spatial reasoning with respect to manifold tasks in different application fields such as landscape planning and design, urban development, environmental analysis and simulation, risk and disaster management, as well as logistics and transportation.

The presented technique can be applied to various visualization scenarios of massive movement data. The proposed multi-scale approach supports different visualization modes, including individual animated trajectory rendering and visualization of aggregation results. This technique facilitates spatial-temporal filtering, selection and highlighting as well as enables detailed inspection of specific movement trajectories in the context of the complete data set (Figure 3). Further, it enables the spatial and temporal exploration of aggregated trajectories using density and difference maps to visualize important analysis aspects such as overall traffic density or average height. The processing results are directly projected onto the digital landscape model to visualize and correlate relations between individual movements and aggregated data (Figure 4).

As a use case, we showed how to apply this technique to air-traffic trajectory visualization. The presented technique is easily applicable to other kinds of movement data such as traffic data in general (e.g., car movements, or naval vessel movements), pedestrian movements in cities or smaller areas, or animal movements.

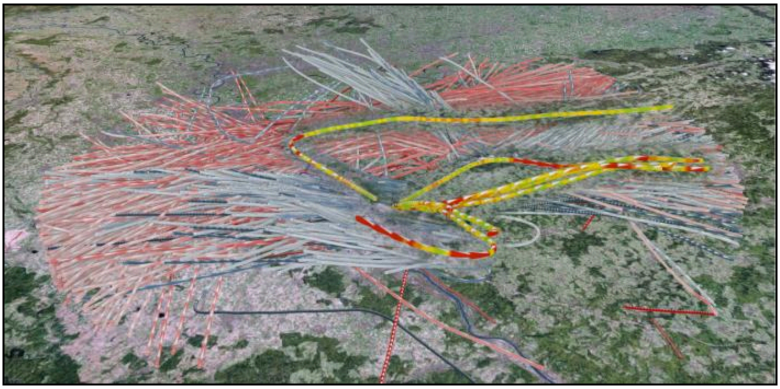

Fig. 3: Visualization of massive air-traffic trajectories, displaying approaching and departing airplanes, with detailed information on a number of selected trajectories, encoding acceleration in color.

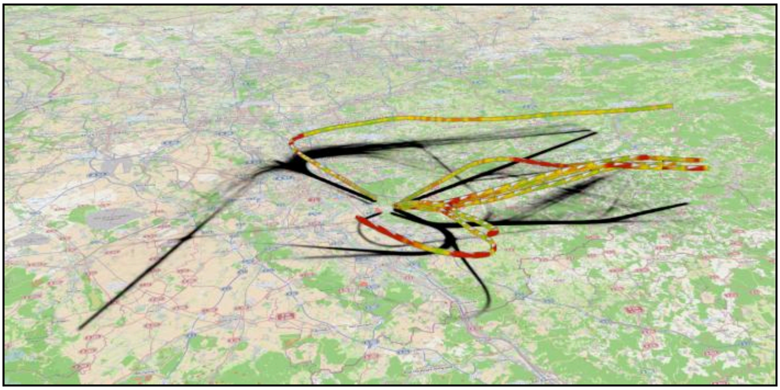

Fig. 4: Comparison of individual trajectories with aggregated movement data depicted as a density map.

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